ROMS/TOMS Tangent Linear and Adjoint Models: Testing and Applications

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LONG-TERM GOALS

Our long-term technical goal is to develop and test the Tangent Linear Model (TLM), Representer Model (RPM), and Adjoint Model (ADM) versions of ROMS (Regional Ocean Modeling System) and TOMS (Terrain-following Ocean Modeling System) for variational data assimilation, ensemble forecasting, and stability analysis. The primary focus is to develop a general platform for strong and weak constraint 4D Variational data assimilation (4DVar); to develop an ensemble prediction capability based on optimal perturbations and stochastic optimals; and to develop stability analysis tools based on eigenmodes and singular vectors to explore the role of environmental stochastic forcing in shaping ocean circulation. Our long-term scientific goal is to model and predict the mesoscale circulation and the ecosystem response to physical forcing in the various regions of the World Ocean through state estimation.

OBJECTIVES

The objectives and scientific goals of the proposed research are:

1. To explore the factors (*e.g.* uncertainties in initial conditions versus those in surface forcing and boundary conditions) that limit the predictability of the circulation in regional ocean models in a variety of dynamical regimes;
2. To develop state-of-the-art variational data assimilation platforms (strong and weak constraint 4DVar) and gain experience in regional ocean applications;
3. To develop ensemble prediction techniques for regional ocean models.

APPROACH

This is a collaborative effort involving Dr. Andrew M. Moore at University of California at Santa Cruz, Drs. Arthur J. Miller and Bruce D. Cornuelle at the Scripps Institution of Oceanography, and Dr. Emanuele Di Lorenzo at the Georgia Institute of Technology. To address the aforementioned goals and objectives, we are using a newly developed suite of tools that utilize ROMS/TOMS tangent linear and adjoint models. These models and tools were developed under the support of previous ONR funding.

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To address objective (**1**), we are using the ideas of Generalized Stability Theory (GST) in order to identify the most unstable directions of state-space in which errors and uncertainties are likely to grow. Specifically, for initial and boundary condition errors we compute the singular vectors of the TLM propagator, while for surface forcing we compute the stochastic optimals. By examining the details and dynamics of these structures we can learn much about the factors that limit the predictability of the circulation.

To address objective (**2**), we are using several 4-dimensional variational data assimilation schemes that have been developed for ROMS/TOMS. For cases in which the dynamics are imposed as a strong constraint (*i.e.* no model error assumed) we use an incremental 4DVar approach (IS4DVAR) similar to that used operationally at some numerical weather prediction centers. In the case where errors are admitted in the model, we use an indirect representer-based weak constraint 4DVar algorithm (W4DVAR) and a weak constraint Physical Space Analysis System (W4DPSAS). W4DVAR is based on the Oregon State University Inverse Ocean Model (IOM) of which ROMS/TOMS is also a component (Di Lorenzo et al, 2006; Muccino et al, 2006). The IOM requires an additional version of the model that computes a finite amplitude linear estimate of the total state of the system as opposed to perturbations about some existing solution of the nonlinear ROMS. This second linearized form of ROMS/TOMS (denoted here as RPM) has been developed under a separate NSF funded effort.

To address objective (**3**), we will use the optimal structures identified in (**1**) using GST to construct ensembles of model forecasts following the approach used operationally at some numerical weather prediction centers.

WORK COMPLETED

Since the start of this current award the following tasks have been completed:

a. Rewritten the hand-coded TLM, RPM, and ADM algorithms of ROMS/TOMS from F77 to F90/F95 to facilitate multiple levels of nesting, parallelization and improve computational efficiency. The TLM, RPM and ADM are approximately 2.5, 2.6 and 2.8 times more computationally expensive than the Nonlinear Model (NLM). These algorithms were updated to the latest version of ROMS/TOMS framework, tested and distributed to selected beta-testers around the world on May 15, 2006.

b. Parallelized TLM, RPM, and ADM models and their associated drivers. The TLM and RPM can be run in either shared-memory (OpenMP) or distributed-memory (MPI). Currently, the ADM can be only run in distributed-memory because its hand-written construction violates shared-memory mutual exclusion rules between tiles. The TLM and RPM have a parallel structure identical to the NLM. The ADM required adjoint communication exchanges between parallel domain decomposition tiles.

c. Developed and tested the strong constraint, incremental 4DVar (IS4DVAR) following the approach of Courtier et al. (1994). The modeling of the background error covariance uses the generalized diffusion method proposed by Weaver and Courtier (2001). The free parameters controlling the shape of the Gaussian correlation for each state variable are the horizontal and vertical decorrelation length-scales and the diffusion coefficients. The diffusion operators for each state variable are solved explicitly and implicitly. Since the oceanic vertical decorrelation scales are much smaller than the horizontal, the implicit algorithm is preferable and cheaper. It is unconditionally stable for any vertical convolution time-step. The spatially dependent normalization coefficients used to convert the covariance matrix into a correlation matrix are computed using the exact (expensive) or randomization (cheaper) methods (Weaver and Courtier, 2001). These normalization coefficients ensure the diagonal elements of the background error covariance to be equal to unity. After extensive testing with idealized twin experiments, we are now working with realistic data assimilation experiments and state estimation in our US east and west coast, Gulf of Mexico, Caribbean Sea, and East Australia Current applications. We are assimilating various types of data including altimetry, SST from satellites, CTD, XBT, ADCP, and gliders.

d. Developed the weak constraint 4DVar (W4DVAR) single and multiple drivers using the indirect representer approach described in Chua and Bennett (2001). The multiple driver option is used to interface with the IOM framework and developed under separate NSF/ITR funding. As in IS4DVAR, the model error covariance is modeled with the generalized diffusion operator. Currently, we are using the W4DVAR drivers in our US west coast and Intra-Americas Sea applications.

e. Developed a weak constraint 4D-PSAS (W4DPSAS) driver. The PSAS algorithm is similar to W4DVAR but with the RPM replaced with the NLM. That is, the representer functions are not explicitly computed. The PSAS acronym is misleading but it is retained for historical reasons. As in W4DVAR, the minimization is in observation space. Courtier (1997) shows the duality between 4DVar and PSAS. Both algorithms produce identical results if the measurement functional is linear and the background and observation error covariance are the same.

f. Developed an adjoint sensitivity driver to compute the response of a chosen function of the model circulation to variations in all physical attributes of the system.

g. Developed an optimal observation driver that can be used in adaptive sampling to help design observational networks and improve ocean prediction. The adaptive observation strategies are based on the sensitivities of ocean forecasts to a chosen functional (measurement) of the circulation in the area of interest. This driver is an enhanced adjoint sensitivity driver, but the tangent linear model is now used to propagate the analysis and determine the optimal location of the observations.

h. Developed a new stochastic optimals driver in terms of the seminorm of the chosen functional to study the influence of stochastic variations (biases) in ocean forcing.

i. Updated and parallelized the Generalized Stability Theory (GST) drivers used to study the dynamics, sensitivity, and stability of the ocean circulation to naturally occurring perturbations, error or uncertainties in the forecasting system, and adaptive sampling.

RESULTS

Four different geographic areas have been identified for study and were chosen because of existing modeling efforts using ROMS/TOMS. These are the Southern California Bight (SCB), the entire east coast of the United States, the Intra-America Sea (IAS) with particular emphasis in the Caribbean, and the East Australia Current (EAC).

We are currently carrying out ocean state estimation in the EAC for a two year period starting on January 2001. ROMS is forced with NOGAPS winds and clamped to temperature, salinity and geostrophic currents climatology at the open boundaries. We are assimilating SSH altimetry (7-day averaged AVISO), daily best SST (CSIRO HRPT), and a few available XBT surveys. Two different sequential, strong constraint 4DVar experiments have been conceived to examine the impact of assimilating: (I) SSH and SST; and (II) SSH, SST, and XBT. The assimilation window is 7-days and the estimated initial conditions are used to run the nonlinear model for 7-day hindcasts. The ocean state at the end of the hindcast becomes the first guess (background state) for the next assimilation cycle. We have over 100 assimilation cycles for each experiment and have identified

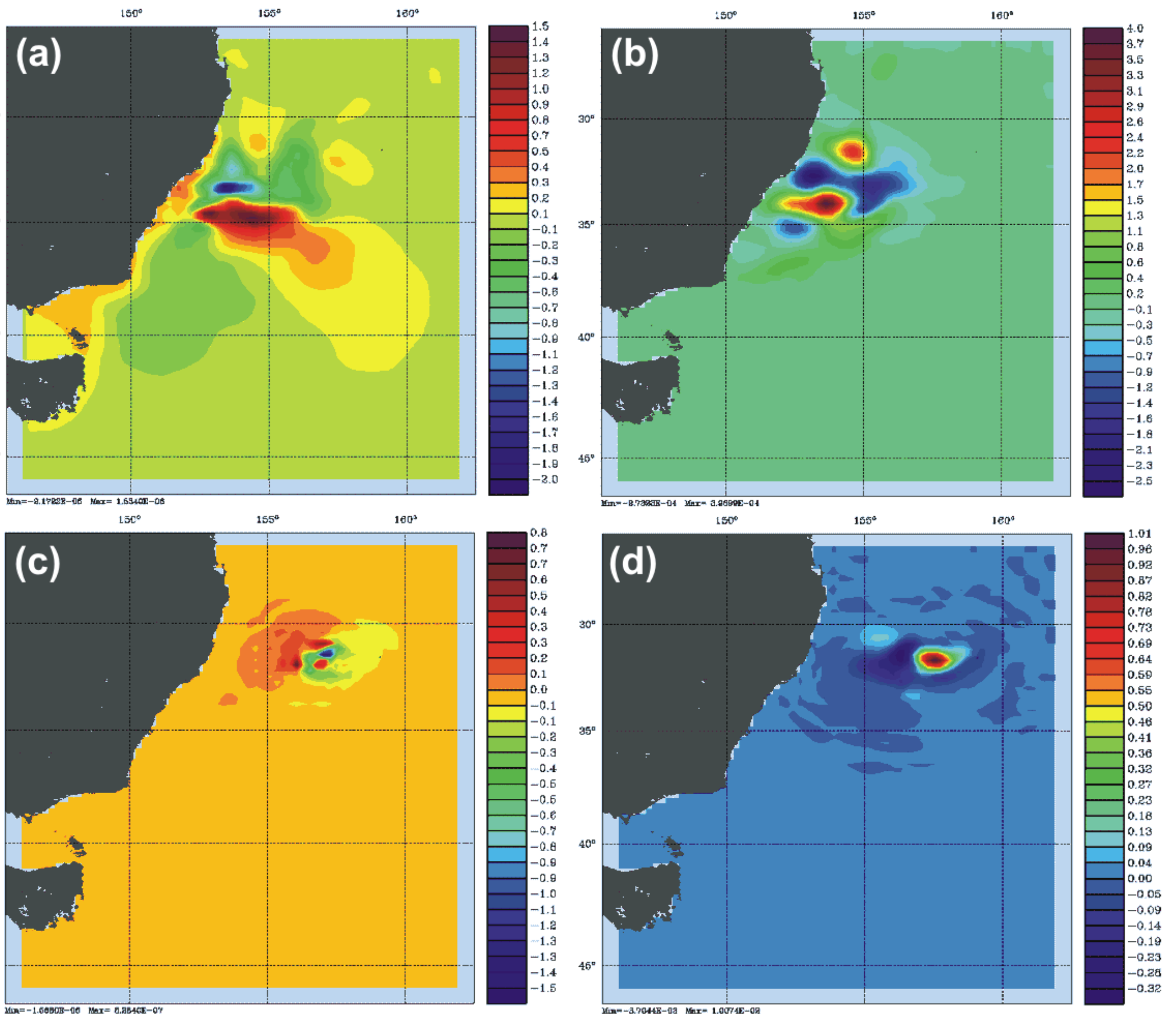

Figure 1. Perturbation sea surface height fastest growing singular vectors for assimilation experiment I (SSH /SST): (a) initial, (b) 10-day interval; and assimilation experiment II (SSH/SST/XBT): (c) initial, (d) 10-day interval.

the hindcasts where the model skill deteriorates rapidly. The ROMS GST package is used to analyze such hindcasts by computing the optimal perturbations for 3-, 5-, and 10-days periods. An example of such analysis is shown in Figure 1. It displays the most energetic SSH optimal perturbation singular vectors (SV) for experiments I and II. Figure 1a,b shows the initial and final 10-day perturbations for the fastest growing SV in experiment I. Figure 1c,d shows the corresponding perturbations for experiment II. Notice that in both experiments the perturbation energy has grown around 100-fold in 10-days. The SVs for experiment I are confined to the coast; exhibit larger spatial scales; and are predominantly barotropic. On the other hand, the SVs for experiment II are located offshore; have smaller spatial scales, and are baroclinic. Clearly, the perturbation energy growth is due to barotropic instability in experiment I and baroclinic instability in II. These results indicate that actually subsurface observations are needed to better constrain the circulation in the EAC 4DVar estimation. Luckily, the few XBT observations available for this hindcast period are located in the area of rapid energy growth (Figure 1a,b). This type of analysis becomes important for adaptive sampling strategies.

An ensemble forecast experiment is carried out by perturbing the estimated initial conditions from assimilation experiments I and II along the most unstable directions of the state space. The first 10 members of the optimal perturbations spectrum are used to generate a 10-member ensemble forecast using a Monte-Carlo approach. Figure 2 shows the SSH height ensemble for 1-, 8-, and 15-day forecasts for experiment I (a,b,c) and II (d,e,f), respectively. The ensemble mean is contoured in color and the grey-contours indicate the SSH evolution for ensemble member. Notice that by day 15 (Figure 2c) the spread is higher in experiment I when compared with II (Figure 2d).

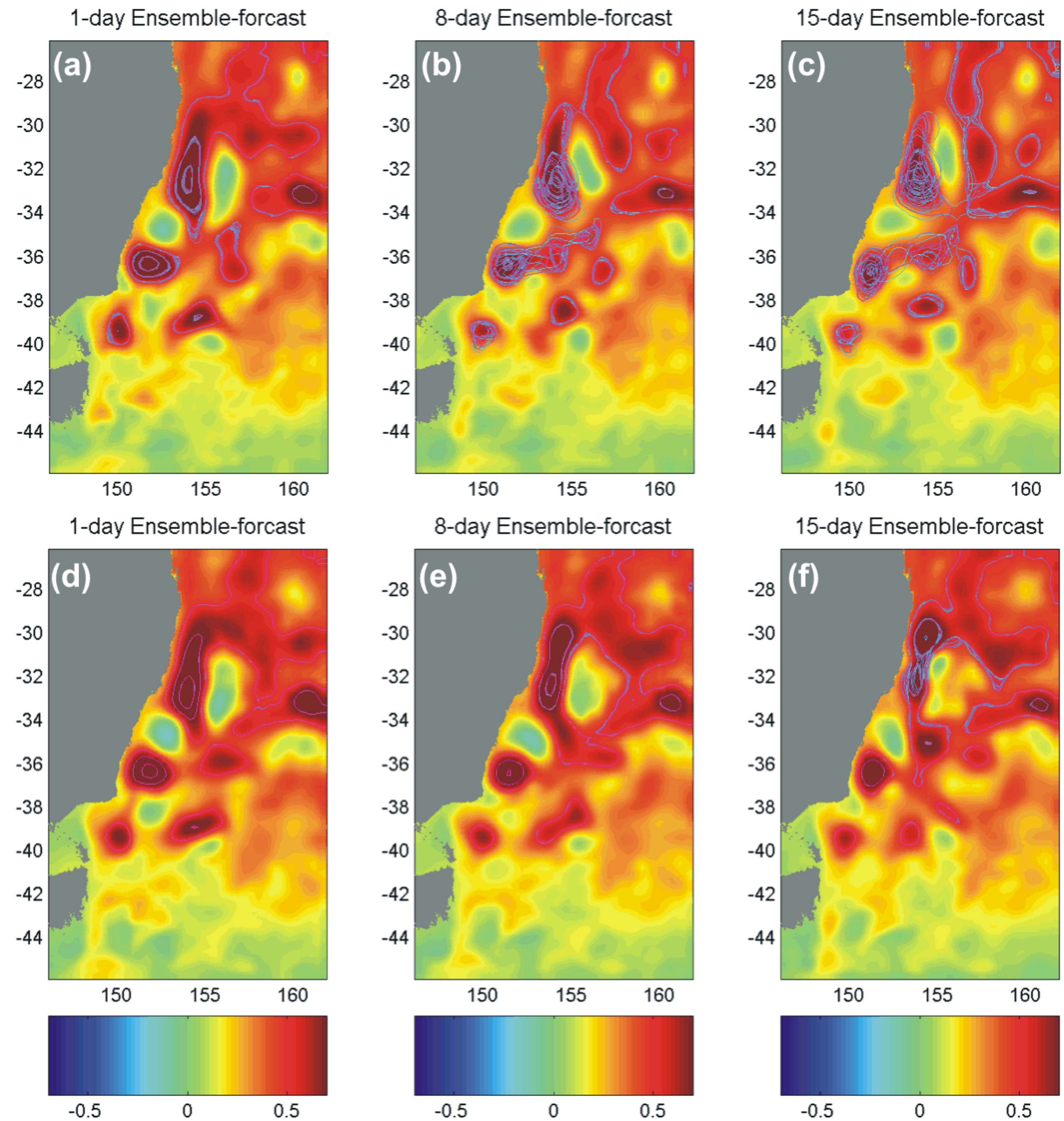

Figure 2. Sea surface height 1-, 8-, 15-day ensemble forecasts for assimilation experiments I (a,b,c) and II (d,e,f). Each ensemble member (grey-contours) is overlaid on the ensemble mean (color).

These results indicate that assimilating subsurface information in the EAC increases the predictability window. The error in SSH is small after a two-week forecast.

IMPACTS/APPLICATIONS

The newly developed ROMS/TOMS adjoint-based platforms are powerful tools for ocean prediction, adaptive sampling, and understanding the underlying circulation dynamics.

TRANSITIONS

The work completed here will be part of the ROMS/TOMS utilities that will be freely available to both research and operational communities.

RELATED PROJECTS

The work described here is in collaboration with Dr. Andrew Moore at University California at Santa Cruz, Drs. Arthur Miller and Bruce Cornuelle at the Scripps Institution of Oceanography, and Dr. Emanuele Di Lorenzo at Georgia Institute of Technology. These investigators are supported by the following grants:

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